

Non-universal Gaugino mass models under the lamppost of muon (g-2)

Joydeep Chakraborty,^a Arghya Choudhury,^b Subhadeep Mondal^b

^a*Department of Physics, Indian Institute of Technology, Kanpur-208016, India*

^b*Regional Centre for Accelerator-based Particle Physics,
Harish-Chandra Research Institute, Allahabad 211019, India*

E-mail: joydeep@iitk.ac.in, arghyachoudhury@hri.res.in,
subhadeepmondal@hri.res.in

ABSTRACT: In unified $\mathcal{N} = 1$ supergravity scenario the gaugino masses can be non-universal. The patterns of these non-universalities are dictated by the vacuum expectation values of non-singlet chiral super-fields in visible sector. Here, we have analysed the model independent correlations among the gaugino masses with an aim to explain the $[1 \div 3]\sigma$ excess of muon (g-2) (Δa_μ). We have also encapsulated the interconnections among other low and high scale parameters, compatible with the collider constraints, Higgs mass, relic density and flavour data. We have noted that the existing non-universal models are not capable enough to explain Δa_μ at $[1 \div 2]\sigma$ level. In the process, we have also shown the impact of recent limits from the searches for disappearing track and long lived charged particles at the LHC. These are the most stringent limits so far ruling out a large parameter space allowed by other constraints. We have also performed model guided analysis where gaugino masses are linear combination of contributions coming from singlet and non-singlet chiral super-fields. Here, a new mixing parameter has been introduced. Following the earlier methodology, we have been able to constrain this mixing parameter and pin down the promising models on this notion.

KEYWORDS: LHC, Non-Universal Gaugino, GUT, muon (g-2).

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1 Introduction

Supersymmetry (SUSY) is one of the most promising beyond Standard Model (BSM) scenarios that solves the gauge hierarchy problem, stabilizes the Higgs mass and also addresses some of the other shortcomings of the SM. It also provides a weakly interacting massive particle (WIMP) which can be a viable cold dark matter (DM). In R-parity conserving scenario, the lightest supersymmetric particle (LSP) happens to be that DM candidate. From unification view point, SUSY shows an improvement over the Standard Model (SM) predictions with a consistent grand unification (GUT) scale.

In global minimal supersymmetric standard model (MSSM), the gauge group is same as that for the SM, but the particle content is extended in form of the supersymmetric partners. In unbroken SUSY scenario, the supertrace¹ vanishes exactly which is due to the degeneracy in the spectrum and equality in fermionic and bosonic degrees of freedoms in theory. However, so far experimental data suggests that all the SUSY particles must be heavier than their respective SM partners. Thus the supertrace must be non-vanishing and, in general, proportional to the SUSY scale. In other words, we can say that SUSY can be realized in nature only in broken form². So, the important question that rises in this context is following: what is the SUSY breaking mechanism? So far we have failed to pin down any specific breaking scenario, rather fenced by different possibilities. These mechanisms can be broadly classified into two categories: spontaneous³ and explicit breaking by addition of the SUSY breaking soft terms in the Lagrangian [3–9]. The later one is not forbidden by any physical principle but it leads to enormous number of free parameters (more than 100) in the theory and spoils the beauty of it. We are not elaborating this possibility as this is not the prime moto of this paper. The outcome of spontaneous breaking depends on which field is getting vacuum expectation value (VEV). However, as we know, spontaneous breaking does not change the property of the action. Hence the supertrace which is a signature of the Lagrangian, is kept unmodified. This is against the experimental observation as mentioned before and thus ruled out. Again if we start with an exact SUSY Lagrangian, we are bound to break SUSY only spontaneously [3, 4]. This dilemma can be resolved if one breaks SUSY in the hidden sector. This information of SUSY breaking can be brought to the visible sector by different messengers, giving rise to different models, such as gravity-, gauge-, anomaly-mediated SUSY scenarios. For the sake of our work, let us further proceed our discussion on the gravity mediated SUSY breaking scenario: $\mathcal{N} = 1$ SUGRA [10–21]. In the minimal SUGRA (mSUGRA) framework, there are only 5 free parameters compared to over 100 in the general MSSM case: universal scalar mass (m_0), universal gaugino mass ($m_{1/2}$), $\tan \beta$ (ratio of the up and down type Higgs VEVs $= v_u/v_d$), tri-linear coupling (A_0) and sign of μ term ($sgn(\mu)$). However, it is not necessary for the gauginos to be degenerate at the high scale itself. If the visible sector possesses an unified gauge symmetry, the gauginos may become non-degenerate through the VEV of the GUT breaking scalars [22–34]. Then the high scale input parameters consist of $m_0, M_3, \tan \beta, A_0$ and $sgn(\mu)$, where, M_3 is the mass scale for the $SU(3)_C$ gauginos. This also determines M_1 and M_2 , as they are correlated: $M_1 : M_2 : M_3 = a : b : c$,

¹Supertrace in supersymmetric theory is defined as: $Str = \sum_s (-1)^{2s} (2s+1) Tr(m_s^2)$, where s, m_s are the spin and mass of the particle respectively.

²In passing we would like to draw attention to another view as suggested [1] questioning the necessity of supersymmetry breaking.

³Dynamical supersymmetry breaking is an interesting possibility [2] but is troublesome as it might lead to charge and colour breaking vacua.

where a, b, c depend on patterns of the symmetry breaking. This enriches the possibility of having different correlations among these gaugino masses which lead to different compositions of the LSP at low scale. Thus unlike the mSUGRA case, here, the LSP can be bino, wino, higgsino or admixture of these three states. This allows us to explore wide range of phenomenologies driven by non-universal gaugino masses. The phenomenological aspects of non-universal gaugino mass scenario are discussed in [35–64]. Due to its varieties of LSP configurations, these models have significant impact on the analyses regarding DM searches and muon (g-2) excess. These two issues have been explored extensively within mSUGRA framework. But the present limits on squarks and gluino put severe stringent bounds on mSUGRA parameter space. This results in unavailability of SUSY spectrum within this framework that can explain Δa_μ ⁴ at $[1 \div 2]\sigma$ level respecting flavour constraints.

This has been the motivation of our work. The prime aim of our analysis is to understand the model independent correlations among the MSSM gauginos which can successfully explain the anomalous muon (g-2) excess over the SM, and simultaneously satisfy different experimental bounds at low energy. In this context we have discussed two scenarios: non-universal gaugino & universal scalars, universal gaugino & non-universal scalars. We have extended our former framework by adopting existing SUSY-GUT models and considering the general gaugino spectrum. We also introduce here a new mixing parameter that is related to the superpotentials. We have encapsulated the range of this new parameter while explaining muon (g-2) excess at $[1 \div 3]\sigma$ level.

2 Generation of Gaugino Masses in $\mathcal{N} = 1$ unified SUGRA models

Here, we have briefly reviewed the Lagrangian based discussion on the generation of gaugino masses. In $\mathcal{N} = 1$ supergravity framework, the part of the needful Lagrangian which is associated with the gauge and gaugino sectors is expressed as [13–16, 24–30]

$$\begin{aligned} \mathbf{e}^{-1}\mathcal{L} = & -\frac{\mathcal{F}_{\alpha\beta}}{2}\frac{\overline{\lambda}^\alpha\cancel{D}\lambda^\beta}{2} - \frac{1}{4}\text{Tr}[F_{\mu\nu}\mathcal{F}(\Phi)F^{\mu\nu}] \\ & + \frac{1}{4}e^{-G/2}G^i(G^{-1})^j_i\left[\frac{\delta\mathcal{F}^*_{\alpha\beta}(\Phi^*)}{\delta\Phi^{j*}}\right]\lambda^\alpha\lambda^\beta + h.c., \end{aligned} \quad (2.1)$$

where, $\alpha, \beta, \gamma = [1, \dots, Adj]$ ⁵. Here, we have set $M_{Pl}/\sqrt{8\pi} = 1$. Our nomenclature is following: G, \mathcal{F}, Φ and λ are the Kähler potential, the super-potential, chiral super-fields and gaugino fields respectively.

⁴ Δa_μ denotes the discrepancy between experimentally measured value of muon (g-2) and the SM predicted one.

⁵For $SU(N)$ and $SO(N)$, Adj is defined as $(N^2 - 1)$ and $(N^2 - N)/2$ respectively.

Here, the derivatives of Kähler potential are defined as: $G^i = \frac{\delta G}{\delta \Phi_i}$, $G_j^i = \frac{\delta^2 G}{\delta \Phi^{*j} \delta \Phi_i}$, and $(G^{-1})_j^i$ is the inverse of G_j^i . The chiral function $\mathcal{F}_{\alpha\beta}(\Phi)$ is an analytic function of Φ . These Φ 's are the chiral super-fields belonging to the visible (ϕ) as well as the hidden (z_h) sectors. The chiral field z_h is singlet under the gauge symmetry of the visible sector. The other chiral super-field ϕ is non-singlet under such gauge symmetries. The choices of ϕ are further restricted from the gauge kinetic term $Tr[F_{\mu\nu}\mathcal{F}(\Phi)F^{\mu\nu}]$ which dictates that ϕ can only belong to the symmetric product of two adjoint representations. In this framework, both SUSY and unified gauge symmetry are broken spontaneously. The VEV of z_h (z_h^0) that breaks local SUSY spontaneously is very large ($\sim 10^{19}$ GeV) where the VEV of ϕ (V_{GUT}) sets the GUT scale (M_U). The generic structure of the chiral function, $\mathcal{F}_{\alpha\beta}$, can be given as suggested in [28, 30] (neglecting higher order terms which are more suppressed):

$$\mathcal{F}_{\alpha\beta} = \mathcal{F}_1 \delta_{\alpha\beta} + \mathcal{F}_2 c_{\alpha\beta\gamma} \phi^\gamma, \quad (2.2)$$

where $\mathcal{F}_{1,2}$ are the functions of chiral super-fields of hidden and visible sectors, and $c_{\alpha\beta\gamma}$ are the group theoretic factors. The first term is the canonical term leading to mSUGRA like scenario where all the gauginos are degenerate, i.e., universal. The second term is due to the presence of GUT symmetry breaking scalars which cause splitting in universal gaugino spectrum of mSUGRA leading to non-universal gaugino masses at the high scale itself. The different choices of these ϕ fields lead to possible non-universalities as the high scale boundary conditions. For the purpose of our present analysis, we consider that $\mathcal{F}_{1,2}$ are the only functions of z_h , and ϕ . In Fig. 2.1, we have summarized this whole process through a schematic flow chart.

Once SUSY and GUT are broken, one can recast the gaugino mass terms as

$$M_i = M [P + \delta_i V_{\text{GUT}} Q], \quad (2.3)$$

where the δ_i 's are the group theoretical factors for broken and unbroken generators (see Refs. [28–30] for details) similar to $c_{\alpha\beta\gamma}$ in Eq. 2.2. We can write down $i \ni [j, X]$ where j and X represent the indices for unbroken and broken generators respectively. To understand this better, let us consider the breaking of $SU(5)$ to $U(1)_Y \otimes SU(2)_L \otimes SU(3)_C$ (\mathcal{G}_{MSSM}). As an outcome of this mechanism, 12 generators of \mathcal{G}_{MSSM} are unbroken, and rest of the $(24 - 12) = 12$ generators are broken. In our further analysis, we denote the gauginos corresponding to the broken generators as X and others are associated with index j . Here, P and Q are the functions of z_h^0 , V_{GUT} and derivatives of $\mathcal{F}_{1,2}$, evaluated at $[z_h^0, V_{\text{GUT}}]$. Within SUGRA framework, unfortunately, the exact functional forms of $\mathcal{F}_1, \mathcal{F}_2$ are unknown and same for P, Q . However, in simplified scenario, like mSUGRA, due to absence of GUT group in the visible sector there is no need of non-singlet field ϕ in the theory. This implies that all the δ_i 's are identically zero leading to all the gaugino masses to be degenerate, i.e., universal.

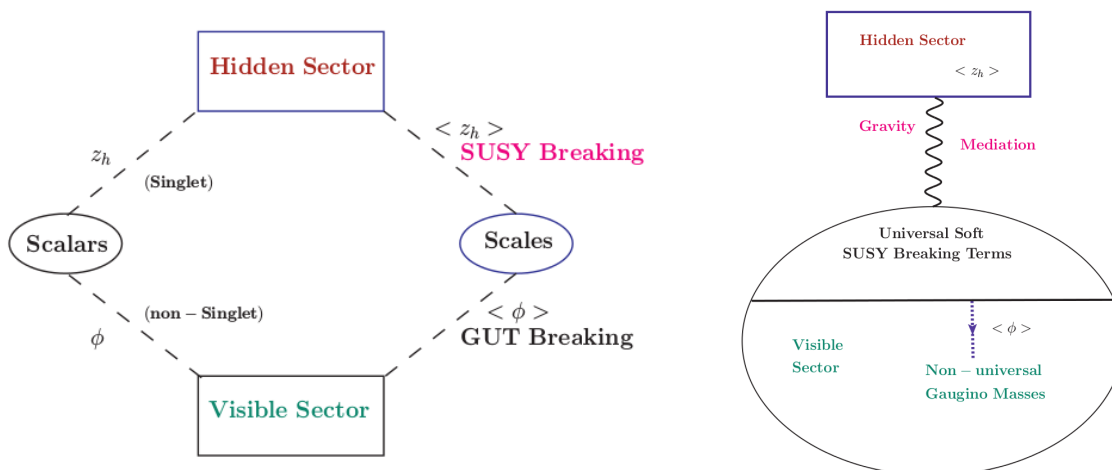


Figure 2.1. Schematic flow chart to demonstrate spontaneous breaking of supersymmetry in the hidden sector through the VEV of the singlet chiral super-field (z_h) and successive breaking of GUT symmetry in the visible sector through the VEV of non-singlet chiral super-field (ϕ). As the outcome of this process, the soft SUSY breaking terms are generated in the visible sector and the gauginos become non-degenerate at the high scale itself.

But within the unified SUGRA framework, the generic form of the gaugino mass is given in Eq. 2.3 which cannot be further simplified to understand the specific correlations among them unless we make some assumption. In Refs. [31–34] it was pointed out from pure phenomenological perspective that if P/Q is negligibly small then the ratio of the gaugino masses are just the ratios of δ_i 's. It has been also argued in Refs. [28, 30] that to stabilise the cosmological constant, the masses of the X -gauginos must vanish and also provide unique mass ratios for MSSM gauginos independent of P and Q . Here, the gaugino masses are automatically non-universal and posses definite non-universal patterns. To complete this discussion, we would like to mention that the generation of gaugino masses in context of supergravity framework was first discussed in Refs. [28–30] for $SU(5)$ unified theory. Later this has been generalised for $SO(10)$ and $E(6)$ GUT groups in Refs. [31–34].

The generic form of gaugino masses, without any further assumption, can be recast as:

$$\mathcal{M}_i = M' [1 + \wp \delta_i], \quad (2.4)$$

where \wp is the ratio of P, Q and can be thought of as a measure of mixing between singlet and non-singlet contributions. We will emphasize more on this mixing parameter, \wp , from muon (g-2) point of view for some specific models.

3 Muon g-2

The precision measurements are leaving very little room for new physics. One of them which has been measured experimentally with an immaculate accuracy is the muon anomalous magnetic moment. In the SM, there exists a tree level contribution to muon(ℓ_μ)-muon-photon(A_ρ) coupling ($ie\overline{\ell}_\mu\gamma^\rho\ell_\mu A_\rho$). Along with that in BSM scenario, the relatively heavier and so far unobserved particles may contribute to this vertex through radiative corrections in the form of an effective operator like ($ie/4m_\mu$) $a_\mu\overline{\ell}_\mu[\gamma^\lambda, \gamma^\rho]\ell_\mu(\partial_\lambda A_\rho - \partial_\rho A_\lambda)$. So far, there is a discrepancy, Δa_μ , among the SM theoretical prediction and experimentally observed value [65, 66]. Thus the BSM contributions, if there is any, have to be fitted within the deviation [67]

$$\Delta a_\mu = (29.3 \pm 9.0) \times 10^{-10}. \quad (3.1)$$

It is expected that SUSY can explain this excess through the exchanges of different particles and that has been one of the motivation for TeV scale SUSY. The loop induced contributions (see Figs. 3.1, 3.2) involving sleptons, neutralinos, charginos and sneutrinos are very important in this regard [68–71]. In the context of general SUSY scenario, muon (g-2) has been discussed in [72–79]. Within the unified SUGRA framework the contributions to anomalous muon magnetic moment are discussed in [79–86].

In this paper, we have started with a framework where all the scalar masses are universal but the gauginos are non-degenerate at the high scale itself. The other parameters, say, $\tan\beta$, $sgn(\mu)$, $A_0(= -2m_0)$, $m_{H_u}^2 = m_{H_d}^2(= m_0^2)$ are chosen suitably. Our intention is to adjudicate the patterns of non-universalities in gaugino masses under the light of Δa_μ at $[1 \div 3]\sigma$ level. In other words, we have used Δa_μ to intrigue unified SUGRA model building.

Computation of the radiative contributions to a_μ is very similar to the generic SUSY scenario. The only difference is in the generation of the low scale SUSY spectrum. Due to the high scale boundary conditions, our scenario is much more constrained. Thus the low scale sparticle spectrum cannot be tuned arbitrarily to fulfil the necessary contributions for muon (g-2). In general the chargino-sneutrino loop (see Fig. 3.2) contributes more dominantly compared to the neutralino-smuon loop (see Fig. 3.1). But this is not always true as these contributions depend on the right-handed smuon ($\tilde{\mu}_R$) mass.

The mass parameters masses of sleptons, neutralinos, charginos and sneutrinos play crucial roles to determine the muon anomalous magnetic moment. The high scale parameters which are involved in these computations are $M_{1,2}, m_0(= \tilde{m}_{L,R}), \tan\beta, A_0$ and $sgn(\mu)$. The dependence of Δa_μ on $\tan\beta$ is linear which is due to the requirement of chirality flipping through the Yukawa couplings. Thus Δa_μ is very sensitive to $\tan\beta$ and larger value of $\tan\beta$ is favoured to produce bigger contribution to Δa_μ . However, we are forced to respect the constraints from flavour

data and need to be careful while considering large $\tan\beta$. We would like to notify that the choice of $\text{sgn}(\mu)$ is also restricted as $\mu M_3 < 0$ is severely constrained from the measurement of $\text{BR}(b \rightarrow s\gamma)$. Also note that Δa_μ prefers $\text{sgn}(\mu) > 0$. Hence throughout this work, we only consider $\mu > 0$.

In our analysis, the scalar masses are universal at the high scale, thus the splitting between left- and right-handed sleptons are not large. However, through the renormalisation group evolutions, the off-diagonal terms in the slepton mass matrix can be generated and that may lead to an open possibility of having contributions from all generations of sleptons. Again if the μ term, i.e., the higgsino mass parameter is larger than the masses of the left-handed smuons then the masses of the right-handed smuons play crucial role (see left-top of Fig. 3.1). Then the contribution to Δa_μ from this diagram decreases as mass of the right-handed smuon increases. Note that this effect is only visible if the diagrams in Fig. 3.1 dominate over the one in Fig. 3.2. In general, if the lightest neutralino, lighter chargino, left- & right-handed smuons and sneutrinos are nearly degenerate (within few tens of GeV) and also μ term is of the same order, then the following diagrams dominantly contribute positively to a_μ (see top-left of Fig. 3.1 and Fig. 3.2). Note that if the sneutrinos are lighter than the smuons and also the μ term (as in our case), the dominant contribution may come from Fig. 3.2.

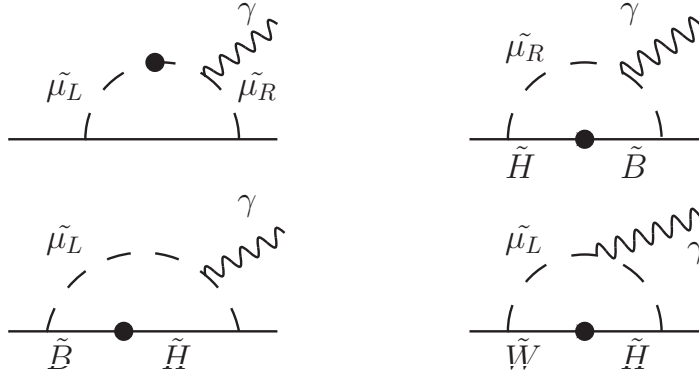


Figure 3.1. Feynman diagrams that contribute to muon (g-2) involving neutralinos ($\tilde{B}, \tilde{W}, \tilde{H}$) and smuons ($\tilde{\mu}_{L,R}$).

4 Collider, Low energy and Dark Matter Searches Constraints

The recent searches at LHC continue to put severe exclusion limits on sparticle masses and couplings. In case of SUSY, the parameter space is very sensitive to the mass of the observed Higgs boson and other flavour data. Along with these collider constraints one cannot ignore the impact of DM searches (direct, indirect) and also

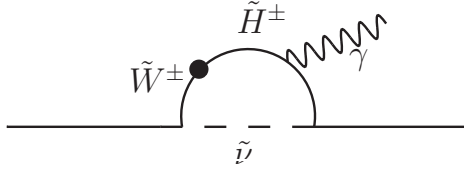


Figure 3.2. Feynman diagrams that contribute to muon (g-2) involving charginos ($\tilde{W}^\pm, \tilde{H}^\pm$) and sneutrino ($\tilde{\nu}$).

needs to respect the upper bound of relic density. Here, we catalogue the imposed constraints in our analysis.

4.1 Collider Constraints

In this section, we first discuss the limits obtained from LEP (I & II) and then from the LHC searches. The latest search results for long-lived charged particles and disappearing tracks at the LHC are also crucial for our study. Thus we prefer to discuss these separately at the end of this subsection.

LEP exclusions:

We have implemented the following LEP constraints on the masses of sparticles:

- sleptons: $m_{\tilde{l}_L}, m_{\tilde{l}_R} > 100.0$ GeV where $l = e, \mu$; $m_{\tilde{\tau}_1} > 86.6$ GeV,
- lighter chargino : $m_{\tilde{\chi}_1^\pm} > 103.5$ GeV.

More details on these exclusions are discussed in Ref. [87].

LHC exclusions:

After the completion of LHC Run-I, the exclusion limits on the sparticle masses are much more stronger now. More specifically, due to the large production cross-sections, constraints on the masses of strongly interacting SUSY particles (e.g., gluino, squarks) are more restrictive. Both ATLAS and CMS collaborations have updated their analyses in n -leptons+ m -jets (with or without b -tagging)+ \cancel{E}_T (where n and m can take values 0, 1, 2,...) channels for supersymmetric models like mSUGRA, cMSSM and other simplified SUSY scenarios. Apart from the production cross-section, all the limits also crucially depend on the branching ratios (BRs) and mass separations among the mother and daughter particles.

In SUGRA type scenarios, all the gaugino ($\tilde{\chi}_1^0, \tilde{\chi}_1^\pm, \tilde{g}$) masses are correlated: either universal or non-universal at the GUT scale itself. As we are focussing on non-universal gaugino scenario, we have incorporated the limits coming from the

searches of simplified models with suitable changes⁶ for the sake of our analysis rather using direct mSUGRA bounds.

We have mentioned earlier that at the electro-weak (EW) scale, the contributions to muon (g-2) are controlled by the following parameters: masses of sleptons, lighter chargino, lightest neutralino and their compositions. As we are working within an unified framework at the high scale, the low scale spectrum is correlated with the high scale soft SUSY breaking terms and the hierarchy in low scale spectrum is determined by other parameters too. For example, one can accommodate light sleptons even satisfying present limits on heavy gluino ($m_{\tilde{g}}$) and squarks ($m_{\tilde{q}}$) masses.

Higgs mass: We allow only those high scale parameters that lead to the lightest Higgs boson mass to be: $M_h = (122 \div 128)$ GeV considering a theoretical uncertainty of ~ 3 GeV[88, 89].

Limits on chargino and neutralino masses: Most of the LHC analyses on direct chargino searches [90, 91] are based on the assumption that the LSP is bino type and the lighter chargino is wino type. For higgsino or mixed type LSP and(or) chargino, the production cross-sections of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ reduce significantly and the limits from trilepton data [90, 91] become much weaker. Again the limits are slightly sensitive to the masses of sleptons⁷ where the LHC collaborations have assumed the slepton masses to be in the midway between $m_{\tilde{\chi}_1^\pm}$ and $m_{\tilde{\chi}_2^0}$. For bino type LSP and wino type lighter chargino, we have implemented the conservative limits in our analysis. Here, we have supplemented the mass limits mentioning specific hierarchical scenarios:

- If $m_{\tilde{t}} < m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}$: for $m_{\tilde{\chi}_1^0} < 300$ GeV, $m_{\tilde{\chi}_1^\pm}$ is excluded below 720 GeV [90, 91]. With an conservative approach having $m_{\tilde{\chi}_1^0}$ in between 300 to 400 GeV, $m_{\tilde{\chi}_1^\pm}$ is excluded in the range of 400 to 700 GeV and for $m_{\tilde{\chi}_1^0} > 400$ GeV, the limits are not applicable[90, 91].
- For heavy slepton scenarios ($m_{\tilde{t}} > m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}$): $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decay via W and Z bosons and the limits on chargino masses are relatively weaker. Again the lighter chargino mass below 420 GeV is excluded with $m_{\tilde{\chi}_1^0} \lesssim 140$ GeV [90].

⁶The results obtained in simplified models are mainly based on the assumption of single particle pair production and one or two step decay modes. Thus one needs to be very careful while using these bounds. The ideal situation would be to calculate the production cross-section for each and every SUSY spectrum and compute the the LHC bounds accordingly. But this is beyond the scope of our analysis. The methodology that has been adapted in this paper is conservative and more importantly not capable enough to alter our predictions.

⁷For varying slepton masses and different mass hierarchies, using the LHC 8 TeV data the limits are revisited in a recent analysis [79]. For revised mass limits in higgsino dominated and(or) mixed chargino scenarios see [92].

- When the $\tilde{\chi}_2^0 \rightarrow h\tilde{\chi}_1^0$ decay mode dominates, the limits become much weaker in the heavy slepton scenarios. Masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are excluded upto 240 GeV for a massless $\tilde{\chi}_1^0$ and the limits are invalidated for $m_{\tilde{\chi}_1^0} > 40$ GeV [93].
- With light third generation slepton ($m_{\tilde{\tau}_1} < m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}$): $m_{\tilde{\chi}_1^\pm}$ upto 380 GeV is excluded for $m_{\tilde{\chi}_1^0} < 85$ GeV [90].

Limits on slepton masses: ATLAS and CMS have searched for charged sleptons (first two generations) from direct production of R(ight) and(or) L(ef)t-type sleptons [91, 94]. ATLAS limits are slightly stronger than that suggested by CMS. Though we have implemented the limits for R-, L- and R=L-types separately, here, we have discussed only that for R=L-type slepton scenario as suggested by ATLAS collaboration using di-lepton search channel [94]. The masses of selectron and smuon (both L- and R-type) are excluded in the mass region between $[90 \div 325]$ GeV with massless $m_{\tilde{\chi}_1^0}$. But the sensitivity of exclusion limit is relaxed once the slepton-LSP mass splitting decreases. For example, for $m_{\tilde{\chi}_1^0} = 100$ GeV, common left- and right-handed slepton masses within $[160 \div 310]$ GeV are excluded. We have adopted the conservative bin wise limits on slepton masses from Fig. 8 of Ref. [94]. For example, slepton mass is excluded within $[268 \div 310]$ GeV for $m_{\tilde{\chi}_1^0} [170 \div 180]$ GeV. We have to keep in mind that these limits exist for LSP mass upto 180 GeV.

Limits on gluino mass: At the LHC, squarks and gluino pair production cross-sections are the largest among other SUSY production channels. The limits on gluino mass ($m_{\tilde{g}}$) crucially depend on the decay properties of \tilde{g} and(or) mass hierarchy between squarks, gluino and other sparticles. If the squarks are lighter than the gluino ($m_{\tilde{g}} > m_{\tilde{q}}$), gluino decays via $\tilde{g}q$ and for such scenario when all squarks and gluinos are produced, the limits on the strong sector of sparticle is most stringent. In mSUGRA (cMSSM) type of scenarios with $\tan\beta = 30$, $A_0 = -2m_0$ and $\mu > 0$, degenerate squarks and gluinos are excluded for masses upto 1.7 TeV at 95 % CL [95]. This limit is applicable for relatively small universal scalar mass m_0 (typically < 1 TeV). For large m_0 and small $m_{1/2}$ (say, $\sim [500 \div 600]$ GeV), gluino decays into $\tilde{t}_1 t$ (note that, the first two generation squarks are much heavier than stop). In such scenarios (with top quark dominated final states), gluino masses smaller than 1.4 TeV are excluded from $[0-1]\ell + 3 b \text{ jets} + \cancel{E}_T$ analysis [96].

In simplified scenarios where gluino decays as: $\tilde{g} \rightarrow \tilde{q}q \rightarrow q\bar{q}\tilde{\chi}_1^0$ (q denotes first two generation squarks) then $m_{\tilde{g}}$ upto 1.5 to 1.55 TeV is excluded for $m_{\tilde{\chi}_1^0}$ upto 600 GeV [95]. When the squarks are very heavy and gluino decays via $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$ (first two generations) then $m_{\tilde{g}}$ below 1.4 TeV is excluded for $m_{\tilde{\chi}_1^0} \lesssim 300$ GeV [95]. All these limits are weakened considerably for the compressed scenarios⁸. For example,

⁸In compressed scenarios, due to small mass difference between the mother and daughter particle, the missing energy (\cancel{E}_T) and transverse momentum (p_T) of the jets or leptons become softer.

when the difference between $m_{\tilde{g}}$ and $m_{\tilde{\chi}_1^0}$ is very small then the exclusion limits on $m_{\tilde{g}}$ reduces to $\sim [550 \div 600]$ GeV (for details see Fig. 10a of Ref. [95]). Even for other scenarios or decay patterns, gluino mass below 1.1 to 1.3 TeV is excluded for relatively light neutralino. The detail reports on SUSY searches regarding various limits for different scenarios, one can consult Refs. [102, 103].

Limits on squarks mass: As discussed earlier, squark masses are excluded upto 1.7 TeV when they are degenerate with gluino. For very heavy gluino scenarios we have implemented the following constraints in our analysis:

- Light flavoured squark masses are excluded below 850 GeV for $m_{\tilde{\chi}_1^0} \leq 350$ GeV [95].
- For the decay modes $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, the exclusion limit on $m_{\tilde{t}_1}$ is upto $[600 \div 700]$ GeV for $m_{\tilde{\chi}_1^0} \leq 250$ GeV [104, 105]. Again when stop decays as $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$, depending on the assumption over the chargino masses, ATLAS and CMS collaborations have excluded stop mass upto $[500 \div 600]$ GeV for $m_{\tilde{\chi}_1^0}$ upto $[200 \div 250]$ GeV [104, 106]. For other decay modes, like $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$; $bW\tilde{\chi}_1^0$; $bf'f'\tilde{\chi}_1^0$, these limits become weaker: $m_{\tilde{t}_1} \geq [240 \div 260]$ GeV [104, 106, 107].
- Mass of sbottom below 620 GeV is excluded at 95% CL when LSP mass is ≤ 150 GeV [108]. For small mass difference between sbottom and LSP, exclusion limit is pushed upto 250 GeV [107].

LHC searches on heavy charged particles:

I. Limits from the search for disappearing track

ATLAS and CMS have recently presented searches for charginos based on the high- p_T disappearing tracks⁹ when the $\tilde{\chi}_1^\pm$ is nearly degenerate with $\tilde{\chi}_1^0$. For $\Delta M = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 140$ (160) MeV, ATLAS and CMS have excluded $m_{\tilde{\chi}_1^\pm}$ upto 500 (270) GeV, see Fig. 5 in [110] (CMS) and Fig. 7 in [111] (ATLAS) for details. We incorporate these exclusion contours obtained by ATLAS and CMS to find the compatible parameter space in our analysis. We have to keep in mind that this limit is applicable only when both the lightest neutralino and lighter chargino are wino like.

Eventually the limits become weaker [97–101].

⁹ In the nearly degenerate scenarios, $\tilde{\chi}_1^\pm$ decays via $\pi^\pm\tilde{\chi}_1^0$ [109]. Due to the small mass difference between $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$, the phase space is limited and the chargino has a significant lifetime. On the other hand, the daughter pion has momentum of ~ 100 MeV which is typically too small for its track to be reconstructed. For charginos that decay inside the tracker volume resulting in a disappearing track.

II. Limits from the search for long lived charged particle

ATLAS collaboration has published the exclusion limits which are out come of searches for heavy long-lived charged particles using 8 TeV data¹⁰ [112]. When the charginos ($\tilde{\chi}_1^\pm$) are nearly degenerate with $\tilde{\chi}_1^0$, i.e., $\Delta M < 135$ MeV, then the exclusion limit on chargino mass becomes more stringent: $m_{\tilde{\chi}_1^\pm} > 620$ GeV [112]. CMS has also presented a similar analysis [113, 114] and the results are in well agreement with ATLAS.

We have noted that these two above mentioned searches play crucial roles and lead to most stringent constraints. We have discussed the impact of these new limits in the following sections. In passing we would like to mention that both these exclusion limits, for nearly degenerate scenarios, crucially depend on the composition of chargino. For higgsino dominated lighter chargino these limits are relaxed considerably.

4.2 Flavour physics data

- The measured value of $\text{BR}(b \rightarrow s\gamma)$ does agree moderately well with the SM prediction and leaves very little room to fit BSM contribution within it. Thus this BR turns out to be a severe constraint whose impact can not be unnoticed. In the MSSM framework, the charged Higgs and chargino exchange diagrams may contribute dominantly to this branching ratio. Since light chargino boosts the required enhancement in Δa_μ , this constraint is very important for our study. However, the contributing diagrams to $\text{BR}(b \rightarrow s\gamma)$ interfere destructively if μ and A_t are of opposite signs. Hence we choose to work with a positive μ and negative A_t throughout. We impose the following constraint for all our points: $2.77 \times 10^{-4} < \text{BR}(b \rightarrow s\gamma) < 4.09 \times 10^{-4}$ (at 3σ level) [115].
- The flavour physics constraint coming from the measurement of $\text{BR}(B_s \rightarrow \mu^+\mu^-)$ puts strong bounds on the MSSM parameter space. For large $\tan\beta$, this branching ratio is proportional to $(\tan\beta)^6$ and inversely proportional to m_A^4 . Thus this is expected to be a critical constraint for large $\tan\beta$ scenarios which are favoured to boost the enhancement in Δa_μ . We impose $0.67 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu^+\mu^-) < 6.22 \times 10^{-9}$ (at 2σ level) [116, 117] as a constraint throughout our study.

4.3 Dark Matter Constraints

I. Relic density

In this work, we have combined WMAP nine year data [118] (2σ bound) with 10% error in theoretical estimation which together propel the upper bound of relic density

¹⁰When charged particles travel with speed slower than the speed of light, they can be identified and their mass can be determined from their measured speed and momentum. ATLAS collaboration has measured these quantities using time of flight and specific ionisation energy loss.

to 0.138. Thus including this range, the 3σ limit as suggested by the PLANCK [119] can be written as:

$$0.092 < \Omega h^2 < 0.138. \quad (4.1)$$

Here, we have adopted the eCMB + BAO + H_0 combined value of Table 4 in Ref. [118].

In our case, lightest neutralino $\tilde{\chi}_1^0$, i.e., the LSP, is the dark matter candidate. Instead of taking the 2σ window, we have respected only the upper limit of Ωh^2 . This is because the DM candidate need not to be necessarily single-component but can also be a multi-component one [120–128]. Although while presenting our benchmark points, we only consider those points which produce the perfect relic density, i.e, $0.1145 < \Omega h^2 < 0.1253$.

II. Direct detection

Apart from the relic density upper limit, we also discuss the implication of direct detection of DM using XENON100 [129] and LUX [130] data on spin independent neutralino-proton $\tilde{\chi}_1^0 p$ scattering cross-section ($\sigma_{\tilde{\chi}_1^0 p}^{SI}$). The t -channel Higgs and s -channel squark exchange diagrams contribute to $\sigma_{\tilde{\chi}_1^0 p}^{SI}$. For heavy squark scenario, the dominant contribution to the cross-section comes from the Higgs exchange diagram [131]. Again if $\tilde{\chi}_1^0$ has sufficiently large higgsino component then $\sigma_{\tilde{\chi}_1^0 p}^{SI}$ may become large [132].

5 Strategy of Analysis

The prime aim of our analysis is to understand the correlations of the MSSM gaugino masses at the high scale itself which can explain the $[1 \div 3]\sigma$ excess of muon (g-2). In the process, we have imposed several constraints, namely, bounds from collider searches and Higgs mass. We have also forced our solutions to respect flavour constraints and the upper bound of relic density. The recent searches for disappearing tracks and long lived charged particles by ATLAS and CMS have put very stringent constraints on the parameter space. In our analysis, particularly, these have played very crucial roles.

To find the model independent correlations among M_1, M_2 and M_3 we have treated these gaugino masses as individual free parameters and varied over wide ranges along with other free parameters, like m_0 and $\tan\beta$. The tri-linear coupling A_0 is taken to be $-2m_0$ and Higgs parameters are set as $m_{H_u}^2 = m_{H_d}^2 = m_0^2$. Using these high scale input parameters, we have generated the SUSY spectrum at low scale and sorted out the parameter space which is compatible with the above mentioned constraints. We have noted the interconnections among different set of high and low scale parameters which have been discussed in detail in later section. The same strategy has been implemented to identify the mixing among singlet and non-singlet contributions for different SUSY-GUT models from muon (g-2) window.

We have generated SUSY spectrum using SuSpect (v2.41) [133]. Further, for DM relic density, direct-indirect detection cross-section and flavour physics calculation we have used micrOMEGAs (v3.6.7) [134] and calcHEP (v3.3.6) [135]. In our analysis, muon (g-2), has been computed using micrOMEGAs.

6 High Scale Non-universality vs Muon g-2

6.1 Non-universal gauginos and universal scalars - model independent analysis

For the sake of our analysis we have supplemented the following input parameters at the high scale: $m_0, M_1, M_2, M_3, \tan \beta, \text{sgn}(\mu)$. All the gaugino mass parameters (M_1, M_2, M_3) are varied randomly and individually at the high scale over a wide range along with other parameters. Below we have listed the ranges of parameters that we have considered for our detailed analysis:

$$\begin{aligned} m_0 &\in (1, 3000) \text{ GeV}; A_0 = -2m_0; \\ M_1 &\in (200, 5000) \text{ GeV}; M_2 \in (-5000, +5000) \text{ GeV}; \\ M_3 &\in (-5000, +5000) \text{ GeV}; \tan \beta \in (1, 60). \end{aligned} \tag{6.1}$$

We have mentioned earlier that the most stringent constraint is appearing for nearly degenerate lighter chargino ($m_{\tilde{\chi}_1^\pm}$) & lightest neutralino ($m_{\tilde{\chi}_1^0}$) scenario. We have noted that for a large part of the parameter space that leads to $[1 \div 2]\sigma$ excess in Δa_μ contain nearly degenerate $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$. Understandably, the 1σ points appear only at the low mass region for $\tilde{\chi}_1^0$ and hence also for $\tilde{\chi}_1^\pm$. In this type of scenario, a consequence of having a wino-like LSP is that the lighter chargino can then be as light as the LSP, provided one has much heavier higgsinos what is exactly what we have here. If $\tilde{\chi}_1^\pm$ mass is just above the $\tilde{\chi}_1^0$ mass so that it can decay into a charged pion (π^\pm) and the LSP, one observes a charge track at the detector. This puts a strong limit on the chargino mass [112]. Now if the degeneracy between the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ masses is such that $\tilde{\chi}_1^\pm$ cannot decay further, its mass limit becomes even stronger [110, 111]. Fig. 6.1 shows the distribution of the measure of mass degeneracy ΔM , as a function of chargino mass. The red, blue and cyan colours represent the points that signify 1σ , 2σ and 3σ excess in Δa_μ respectively. The exclusion limit [110, 111] from long-lived or stable $m_{\tilde{\chi}_1^\pm}$ is shown by the red rectangle at the left bottom corner of the plot. As one can see, all the points below $\Delta M = 135$ MeV are excluded for a chargino mass upto 620 GeV. The region under the slanted black line just above the horizontal red line is excluded from disappearing track search of charged particle [112]. This, by far, appears to be the strongest constraint¹¹ for a wino-like LSP scenario.

¹¹In passing we would like to mention that the numbers we have quoted for the particle masses are obtained from SuSpect [133] which includes one-loop corrections [136]. However, if one incorporate

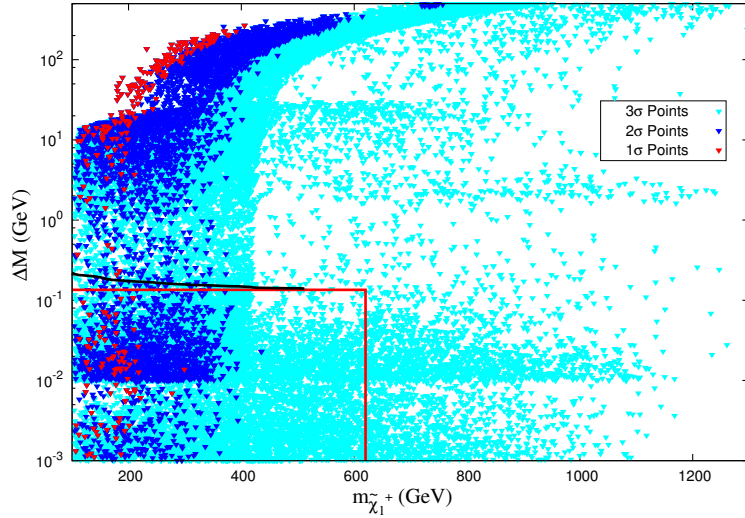


Figure 6.1. Impact of constraints from search for disappearing track and long lived particles, see Sec. 4.1. The region enclosed by the red lines is excluded from long-lived or stable charged particle search. The area under the slanted black line just above the horizontal red line is excluded from disappearing charged track search at the LHC.

From this point onwards, we consider only those points which survive the constraints imposed by the charged track and stable charged particle search besides all the other collider, DM and flavour constraints as described in Sec. 4. Colour coding corresponding to the 1σ , 2σ and 3σ reaches of muon (g-2) remain unchanged in the rest of the paper. In Fig. 6.2 we have shown the distribution of the obtained gaugino mass ratios ($\frac{M_i}{M_3}$, $i=1,2$). We have chosen the range of gaugino masses to encapsulate all the four possible correlations between the ratios M_{13} ($\frac{M_1}{M_3}$) and M_{23} ($\frac{M_2}{M_3}$) including their signs.

Fig. 6.2 is almost symmetric and all the quadrants are in same footing for the purpose of our analysis. Hence it is sufficient to concentrate on one of the four quadrants to understand the nature of the distribution. It is clear that for an enhancement of Δa_μ at $[1 \div 2]\sigma$ level, one needs to have $|M_{23}| \leq 0.7$ and $|M_{13}| \leq 1.1$ excluding $M_{i3} = 0$ for $i=1,2$. From these ratios, one can have an idea about the composition of the LSP under consideration. The mass splitting increases as the contribution of bino component increases in the LSP state. As evident from Fig. 6.1 the mass splitting can be as large as 300 GeV to produce the required $[1 \div 2]\sigma$ enhancement in Δa_μ .

Note that, in this analysis, μ parameter is always relatively higher than M_1 and M_2 at the low scale. This is a consequence of setting the Higgs soft masses (m_{H_d} and the two-loop corrections, the maximum mass splitting can be reduced by 2 to 5 MeV [137] depending upon the SUSY scale. Thus the real impact of this two loop correction will be hardly visible in our Fig. 6.1.

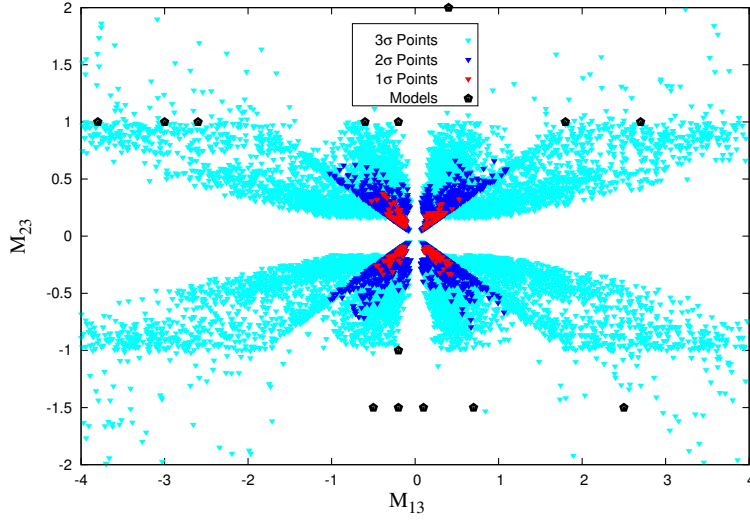


Figure 6.2. Model independent correlations among M_1, M_2, M_3 depending on $[1 \div 3]\sigma$ muon (g-2) excess after satisfying all constraints discussed in the text. The black dots represent the models encapsulated in Tables 1, 2 in Ref. [42]. Here, we have shown only few example model points where other models are out of this frame.

m_{H_u}) equal to m_0 at the high scale. Hence there is no possibility of having a small higgsino component that can contribute to the LSP state. Then it is evident that the most dominating contribution to the muon (g-2) enhancement would come from the processes involving light wino-like $\tilde{\chi}_1^\pm$ and light sleptons. This is one of the reason why the constraints from the search of heavy charged particles are so proactive in our case and rule out a large portion of the parameter space.

The other parameter that plays a very important role in the muon (g-2) calculation is $\tan \beta$. As discussed earlier, the SUSY contribution to muon (g-2) is directly proportional to $\tan \beta$. As a result, large $\tan \beta$, say $[8 \div 35]$, is favoured to achieve 1σ enhancement which is evident from the Fig. 6.3. However, the 2σ enhancement can be obtained for a $\tan \beta$ as low as 5 and as high as 47.

One can infer from the contributing diagrams in Fig. 3.1 that light slepton and LSP are crucial for the enhancement since they only appear as propagators. From Fig. 6.3, we observe that the LSP mass must be lighter than 400 GeV for our purpose. Similarly, Fig. 6.3 puts an upper limit (700 GeV) on the smuon masses beyond which 2σ excess is not found.

Fig. 6.4 shows the correlation between smuon mass and the LSP mass. Since the SUSY contribution to muon (g-2) decreases with the increase of the smuon mass and(or) the LSP masses, we would expect a comet like structure in the smuon-LSP mass plane converging on the lighter side of both the masses, which is reflected in Fig. 6.4 (Left). The plot shows only those points for which $\tilde{\chi}_1^0$ is the LSP, which has been used as a constraint. Note that, a light stau($\tilde{\tau}_1$) can also have an impact

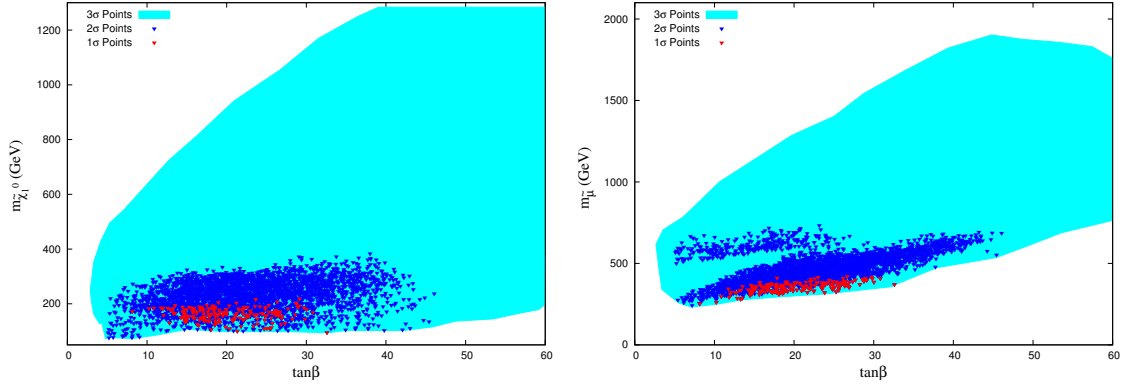


Figure 6.3. Correlations between low scale parameters: (Left panel) lightest neutralino mass ($m_{\tilde{\chi}_1^0}$) vs $\tan\beta$; (Right panel) smuon mass ($m_{\tilde{\mu}}$) vs $\tan\beta$, depending on $[1 \div 3]\sigma$ muon (g-2) excess after satisfying all other constraints discussed in the text. A very similar correlation in $m_{\tilde{\nu}}$ - $\tan\beta$ plane is found as given in plot on the Right Panel. The slepton and sneutrino mass difference varies from 5-20 GeV, indicating that the sneutrino-wino loop in Fig. 3.2 may also contribute significantly.

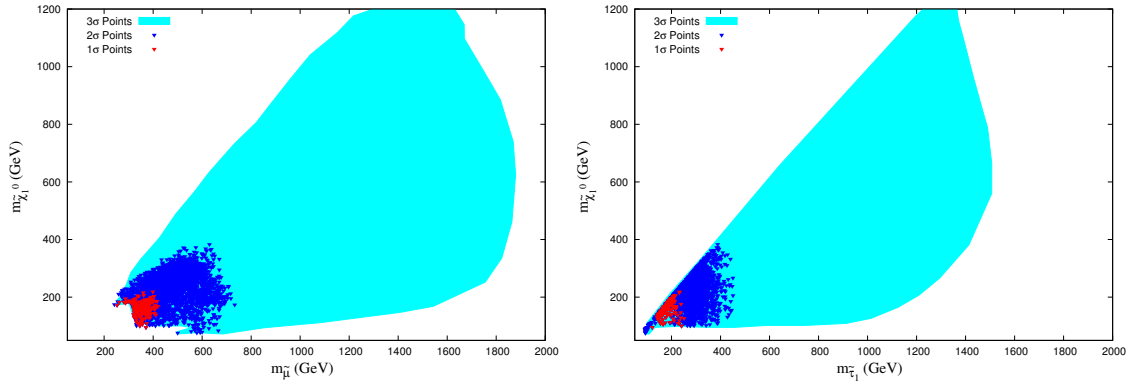


Figure 6.4. Correlations between low scale parameters: (Left panel) lightest neutralino mass ($m_{\tilde{\chi}_1^0}$) vs smuon mass ($m_{\tilde{\mu}}$); (Right panel) lightest neutralino mass vs stau mass ($m_{\tilde{\tau}_1}$), depending on $[1 \div 3]\sigma$ muon (g-2) excess after satisfying all other constraints discussed in the text.

on the muon (g-2) calculation only if there is a sizeable mixing between smuon and stau states. For our choice of $A_0 (= -2m_0)$, we observe that this mixing may vary from negligible amount to as large as 10% depending on the values of m_0 , M_3 and $\tan\beta$. Hence we would expect a sizeable impact of the $\tilde{\tau}_1$ mass in some part of the parameter space, specially, in the low slepton mass regime. Fig. 6.4 (Right) shows the distribution of $m_{\tilde{\tau}_1}$ as a function of $m_{\tilde{\chi}_1^0}$.

Dark Matter Searches

6.1.1 Relic Density

In our analysis, the lightest neutralino ($\tilde{\chi}_1^0$) is the LSP and DM candidate since we have chosen to work in R-parity conserving scenario. We have checked the compatibility of muon (g-2) allowed parameter space with relic density constraint in Fig. 6.5. We consider only those points for which the DM annihilation and(or) co-annihilation are sufficient such that there is no over abundance of the lightest neutralino. As

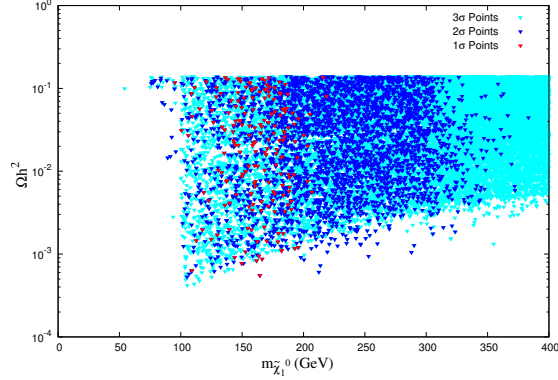


Figure 6.5. Relic density as a function of the mass of the dark matter, i.e., LSP ($\tilde{\chi}_1^0$) depending on $[1 \div 3]\sigma$ muon (g-2) excess after satisfying all other constraints discussed in the text.

evident from Fig. 6.5, most of the favoured points produce a relic density that is much lower than the present upper limit. In our case, the LSP is composed of either bino or wino or an admixture of both.

Dominant contribution to the DM relic density may come from bulk annihilation of $\tilde{\chi}_1^0$ with sleptons (mostly $\tilde{\tau}_1$), co-annihilation of $\tilde{\chi}_1^0$ with the next to lightest supersymmetric particles (NLSPs) $\tilde{\tau}_1$, $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$. Thus the muon (g-2) and DM allowed parameter space can be classified into the following categories:

- **Bulk annihilation:** The pure bulk annihilation region with light sleptons has been ruled out in usual mSUGRA scenario by the LHC constraints. The present exclusion in $m_0 - m_{1/2}$ plane [95, 96] is such that the sfermion is always much heavier than the LSP resulting in suppression of slepton mediated DM pair annihilation cross-sections. However, with non-universal gaugino and universal scalar masses, we have noted that this can be a possibility and specially when $m_{\tilde{\tau}_1} \leq 130$ GeV, it plays an important role in keeping $\tilde{\chi}_1^0$ abundance under the specified limit. If other charged slepton masses are also close to $m_{\tilde{\tau}_1}$, they can participate in bulk annihilation as well with the final state consisting of two charged leptons. Benchmark points (BP) representing such scenario are illustrated in Table 6.1 (see BP1, BP2).

- **stau co-annihilation:** In such scenario, $\tilde{\tau}_1$ is the NLSP and the co-annihilation between $\tilde{\tau}_1$ and LSP is significant to maintain the right relic abundance when $\tilde{\chi}_1^0$ is mostly bino-like. Here the $\tilde{\chi}_1^\pm$ and(or) $\tilde{\chi}_2^0$ states are much heavier. For light $\tilde{\tau}_1$ mass, dominant contribution comes from bulk annihilation process, whereas $\tilde{\tau}_1 - \tilde{\chi}_1^0$ co-annihilation contribution is roughly $\sim 15 - 20\%$ (see BP3 in Table 6.1). With relatively larger $m_{\tilde{\chi}_1^0}$ (see BP4), the co-annihilation processes dominate.
- **chargino co-annihilation:** Here, $\tilde{\chi}_1^\pm$ and(or) $\tilde{\chi}_2^0$ appears as NLSP and consequently $\tilde{\chi}_1^0$ annihilation with these sparticles are responsible to determine the relic density assuming the sleptons are much heavier to take part in co-annihilation. When the mass difference between LSP and NLSP is typically 15-25 GeV, one obtains PLANCK allowed DM relic abundance (see BP5 and BP6). The final states are usually dominated by quarks and gauge bosons. On the other hand, if M_1 is much larger than M_2 , the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ become nearly degenerate with the LSP and they co-annihilate profusely resulting in relic under-abundance.
- **chargino and stau co-annihilation:** In such scenarios, $\tilde{\tau}_1$, $\tilde{\chi}_1^\pm$ and(or) $\tilde{\chi}_2^0$ masses are close to $m_{\tilde{\chi}_1^0}$. Along with bulk annihilation, stau co-annihilation and $\tilde{\chi}_1^\pm$ and(or) $\tilde{\chi}_2^0$ co-annihilation give rise to correct relic density (see BP7 and BP8 in Table 6.1).

6.1.2 Direct and Indirect Detections

In Fig. 6.6 we have shown the distribution of spin independent cross-section (σ_{SI}) as a function of the LSP mass. Note that, all the points shown in these plots obey the relic density upper limit. As evident from the plot, apart from a small part of the

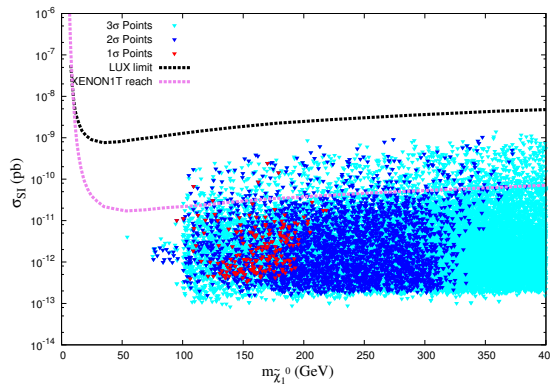


Figure 6.6. Direct detection cross-section as a function of the mass of the dark matter, i.e., LSP ($\tilde{\chi}_1^0$) depending on $[1 \div 3]\sigma$ muon (g-2) excess after satisfying all other constraints discussed in the text.

3σ allowed region, all the other points appear under the most recent exclusion line provided by LUX on σ_{SI} [130] and thus allowed.

The possible contribution to this cross-section comes from t -channel Z -boson, Higgs, squark mediated diagrams or s -channel squark mediated ones. The squarks being heavy do not contribute much. On the other hand, Higgs boson couplings to the first two generation quarks are suppressed. It is well known that within the MSSM framework, the DM-nucleon scattering cross-section may increase alarmingly if the LSP consists of a sizeable higgsino component which enhances its coupling with the Z -boson. Now in our scenario $\mu \gg M_1, M_2$ at low scale for most of the parameter space. Hence the LSP state always has a negligible higgsino component. In large LSP mass region, the μ parameter can be comparable with the other gaugino mass parameters and may enhance the scattering cross-section. However, this region of parameter space is not interesting from the Δa_μ enhancement viewpoint as discussed earlier. We have also shown in Fig. 6.6, the future projected limit of XENON1T [138] experiment. In case of a null result, it will reduce a significant portion of the available parameter space. We have also taken into account the indirect detection cross-section constraints coming from different final states. All our points lie well within the exclusion limits and hence we do not present them in separate plots.

6.1.3 Some Benchmark Points

In this section, we have provided some benchmark points from different regime of the parameter space where Δa_μ , Ωh^2 and flavour constraints all lie within the 2σ ranges of their experimentally measured values. This parameter space is certainly compatible with other collider and low energy constraints mentioned in earlier sections.

In pure bulk (BP1 & BP2) or stau co-annihilation region (BP3 & BP4), $m_{\tilde{\tau}_1}$ is relatively light. Since we are working with universal scalar masses at the GUT scale, this implies either the slepton soft masses are light where the smuons are also expected to be light (see e.g. BP2) or $\tan\beta$ is effectively large. Both these scenarios may enhance Δa_μ which is reflected in BP1 - BP4. Light chargino may also produce the required enhancement provided the sneutrino masses are not too large. BP5 - BP6 represent chargino ao-annihilation region, where $\tilde{\chi}_1^\pm$ is the NLSP. Hence the required enhancement in Δa_μ is obtained even with relatively larger smuon mass. BP7 and BP8 have almost degenerate $\tilde{\tau}_1$ and $\tilde{\chi}_1^\pm$ masses with large values of $\tan\beta$. Hence the combined effect of light chargino and large $\tan\beta$ produce the required enhancement in Δa_μ .

A large $\tan\beta$ results in light stau's in the spectrum. For such low scale spectra, from the production and subsequent decays of the gauginos, one would then expect τ -enriched final states associated with missing energy. Since the τ 's mostly decay hadronically, tagged τ - jets + \cancel{E}_T signature will be the most suitable one to look for such scenarios. However, the LSP-NLSP mass gap being very small, the τ -jet tagging efficiency will be very small.

Parameters	BP1	BP2	BP3	BP4	BP5	BP6	BP7	BP8
M_1	-241.8	-248.5	-330.1	-647.7	-274.4	516.2	373.5	581.4
M_2	299.9	-951.1	-390.0	453.1	187.2	-299.3	233.5	364.3
M_3	1004.1	4573.5	3075.0	1257.9	2275.3	857.1	1396.8	2636.8
m_0	325.3	168.7	346.6	386.9	428.9	483.8	301.1	465.3
$\tan \beta$	29.2	5.2	16.5	30.0	22.1	29.5	21.7	26.7
$m_{\tilde{g}}$	2205.5	9034.1	6269.1	2715.8	4751.0	1911.5	3003.5	5431.5
$m_{\tilde{q}_L}$	1937.9	7606.3	5327.8	2380.4	4074.1	1724.6	2600.7	4642.6
$m_{\tilde{q}_R}$	1938.6	7617.8	5345.4	2379.3	4089.8	1726.6	2609.4	4658.6
$m_{\tilde{t}_1}$	1582.8	6579.8	4594.1	1952.8	3479.0	1339.7	2189.8	3970.2
$m_{\tilde{\ell}_L}$	370.6	500.3	354.7	484.1	409.7	522.9	323.0	485.6
$m_{\tilde{\ell}_R}$	337.8	132.4	354.0	453.5	434.8	520.0	329.4	504.3
$m_{\tilde{\tau}_1}$	121.4	93.3	146.2	288.4	240.0	374.0	170.9	262.7
$m_{\tilde{\nu}_{1,2}}$	362.3	494.7	346.2	477.8	402.2	517.0	313.4	479.4
$m_{\tilde{\nu}_3}$	331.8	494.2	337.8	444.4	384.5	474.0	299.8	453.4
$\tilde{\chi}_1^0$	95.2	75.9	120.9	270.6	100.6	214.1	148.6	235.0
$\tilde{\chi}_2^0$	232.1	734.1	276.2	358.1	114.0	234.7	169.0	263.4
$\tilde{\chi}_1^\pm$	232.1	734.1	276.2	358.1	114.0	234.7	169.0	263.4
μ	1294.8	4863.9	3390.9	1582.2	2637.4	1198.1	1708.4	2990.0
$(g-2)_\mu \times 10^9$	2.64	1.82	2.28	1.42	1.54	1.34	2.64	1.51
$\text{BR}(b \rightarrow s\gamma) \times 10^4$	3.18	3.31	3.31	3.24	3.31	3.11	3.30	3.30
$\text{BR}(B_s \rightarrow \mu\mu) \times 10^9$	3.81	3.07	3.07	3.38	3.08	3.74	3.12	3.09
Ωh^2	0.117	0.115	0.121	0.124	0.116	0.122	0.121	0.120
$\sigma_{SI} \times 10^{13} \text{ (pb)}$	101.0	11.6	4.6	87.1	6.3	281.9	38.6	6.73

Table 6.1. High scale input parameters and the relevant sparticle masses along with the muon (g-2) value for some of the chosen benchmark points satisfying the collider, DM and low energy constraints discussed in earlier sections. All the mass parameters are written in GeV unit.

The squarks and gluinos are in general heavy in these spectra. Since the gluino mass is heavier than all the squark masses, it can decay into all the squark flavours abundantly giving rise to jets + \cancel{E}_T final state. In the usual mSUGRA scenario, on the other hand, usually the gluino decay via stop into multiple top and neutralinos resulting in the multi b -jet final state associated with large missing energy (see, for example, Ref. [96]). Moreover, given the present collider exclusion limits, in mSUGRA, with such heavy color sector as in our benchmark scenarios, it is not possible to achieve a slepton sector light enough to enhance the muon (g-2) value to the desired range.

6.2 Universal gauginos and non-universal scalars - model independent analysis

In this section, we have discussed the other possible high scale scenario in the present context, namely, universal gauginos with non-universal scalars.

If we assume to have a universal mass parameter ($m_{1/2}$) for all the gauginos at the high scale, we expect the LSP to be mostly pure bino like at low scale¹². This is due to the fact that the renormalisation group evolutions determine the gaugino mass ratios to be $M_1 : M_2 : M_3 \simeq 1 : 3 : 6$ at low scale. Hence in such scenario, the $\tilde{\chi}_1^\pm$ contribution to the loop diagrams will be smaller. However, the bino component can be sufficiently light and can contribute to the enhancement, but then the relic density constraint can be a serious problem as the DM pair annihilation cross-section may not be suitable to satisfy proper relic abundance. The non-universal scalar scenario can be useful as it may allow a stau ($\tilde{\tau}_1$) to be light enough which can co-annihilate with $\tilde{\chi}_1^0$ to make up for the annihilation cross-section. An added advantage of having a bino-LSP is that long-lived or stable chargino constraint which proved to be the most severe in the previous case, will not be applicable here.

In this scenario, the high scale input parameters are following: the universal gaugino mass ($m_{1/2}$), slepton mass (m_0) and squark mass (m'_0). The soft Higgs mass parameters, m_{H_d} and m_{H_u} are assumed to be equal to m_0 at the GUT scale. The trilinear coupling, $A_0 (= -2m_0)$ is same as before. We note that this scenario can provide $[2 \div 3]\sigma$ excess in Δa_μ at its best.

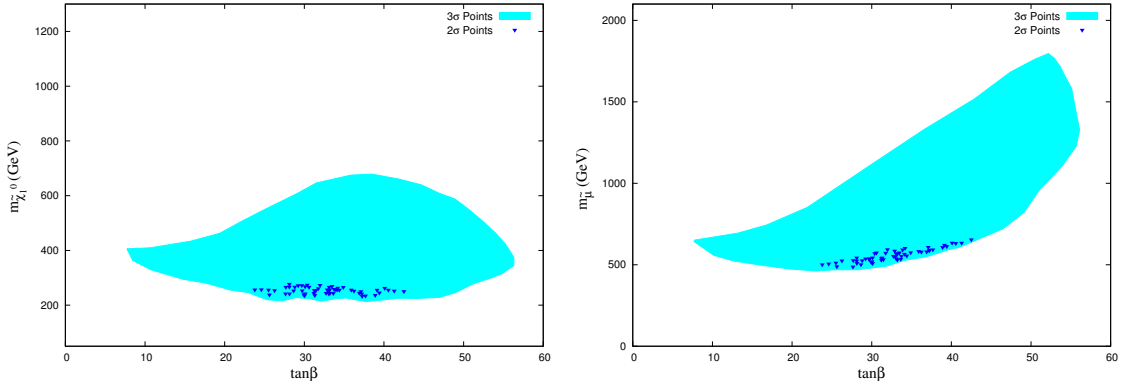


Figure 6.7. Correlations between low scale parameters: (Left panel) lightest neutralino mass ($m_{\tilde{\chi}_1^0}$) vs $\tan \beta$; (Right panel) smuon mass ($m_{\tilde{\mu}}$) vs $\tan \beta$, depending on $[2 \div 3]\sigma$ muon (g-2) excess after satisfying all other constraints discussed in the text. A very similar correlation in $m_{\tilde{\nu}}$ - $\tan \beta$ plane is found as given in plot on the Right Panel. We have not found any parameter space in this scenario that satisfy 1σ excess.

It is evident from Fig. 6.7 that both the slepton and LSP masses are heavier in this scenario compared to the earlier case at the low scale. The collider constraints

¹²We are ignoring the higgsino possibility from the point of our analysis.

for universal gaugino masses combine to produce these mass limits which prevent from achieving 1σ excess of Δa_μ . Assuming a universal gaugino mass at high scale the gluino appears to be roughly six times heavier than the LSP at low scale. Hence imposing a mass limit of ~ 1.2 TeV on the gluino mass for heavy squark scenarios automatically implies that the LSP cannot be lighter than ~ 200 GeV. This scenario is being reflected in Fig. 6.7.

There can be another high scale scenario where both the gauginos and scalars are non-universal. For this case, the collider and DM constraints put very similar lower limits on the LSP and slepton masses to that we obtained for the non-universal gaugino and universal scalar scenario. The LSP composition is also very similar. Hence this scenario does not provide any new features to highlight.

6.3 Non-universal gauginos and universal scalars - model based analysis

We have discussed the generation of gaugino masses in phenomenological $\mathcal{N} = 1$ supergravity scenario in Sec. 2. We have also noted that if the visible sector possesses unified symmetry, then we need a non-singlet scalar to break that symmetry to achieve the SM gauge group. We have further discussed that in presence of a singlet and a non-singlet field in the hidden and visible sectors respectively, the generic gaugino mass terms can be written as $M_i = M' [1 + \wp \delta_i]$ (see Eq. 2.4). This function \wp is the ratio of P, Q (see Eq. 2.3). The detail structure of \wp is not easy to reveal. Thus we have encompassed the numerical ranges of \wp which can explain the muon (g-2) excess successfully at $[1 \div 2]\sigma$ level. The MSSM gaugino mass ratios at the high scale is depicted as:

$$M_1 : M_2 : M_3 = (1 + \wp \delta_1) : (1 + \wp \delta_2) : (1 + \wp \delta_3). \quad (6.2)$$

Earlier in Ref. [42], 25 different phenomenological models were analysed under the impression of dark matter search results. Their contributions from the singlet scalar was neglected and prime focus was on the non-universal part only. We have revisited those models with their generic structures and from muon (g-2) point of view. Here, we have adjudged those non-universal models and checked which among them can successfully explain $[1 \div 2]\sigma$ excess of Δa_μ (see Table 6.2). We have analysed these models to find out the ranges of \wp which is a measure of weighted mixing between singlet and non-singlet contributions. Note that among those 25 models (see Ref. [42]), only 6 can successfully explain observed muon (g-2) excess at $[1 \div 2]\sigma$ level after including the singlet contribution. Few models can provide 3σ excess but we are not quoting those here. Note that, if this singlet contribution is neglected, all those 25 models fail to explain Δa_μ excess at $[1 \div 2]\sigma$ level.

Fig. 6.8 describes the correlation between M_1/M_3 and \wp for different models. There are certain ranges of \wp for which there exist discontinuities in M_{13} which are outcome of the fact that within that range M_{23} or M_{13} vanishes. This happens

Model Number	$M_1 : M_2 : M_3$ (at M_X)	Symmetry Breaking Patterns
1	$-1/5 : -1 : 1$	$E(6) \xrightarrow{(35,1) \subset 650} (SU(6) \otimes SU(2)_R)$
2	$19/10 : 5/2 : 1$	$SO(10) \xrightarrow{(1,1) \subset 770} (SU(4) \otimes SU(2)_R)$
3	$1/10 : -3/2 : 1$	$E(6) \xrightarrow{(54,0) \subset 650} (SO(10) \otimes U(1))_{flipped}$
4	$-1/5 : -3/2 : 1$	$E(6) \xrightarrow{(210,0) \subset 650, 2430} (SO(10) \otimes U(1))_{flipped}$ $(SO(10) \otimes U(1))_{flipped} \xrightarrow{(24) \subset 210} SU(5)$
5	$-1/2 : -3/2 : 1$	$SO(10) \xrightarrow{(24) \subset 54, 210, 770} SU(5)$ $SO(10) \xrightarrow{(24,0) \subset 54} (SU(5) \otimes U(1))_{flipped}$ $SO(10) \xrightarrow{(1,1) \subset 54} (SU(4) \otimes SU(2)_R)$
6	$7/10 : -3/2 : 1$	$SO(10) \xrightarrow{(24,0) \subset 210} (SU(5) \otimes U(1))_{flipped}$

Table 6.2. Gaugino mass models that can explain $[1 \div 3]\sigma$ excess of muon (g-2). Other models are not compatible with $[1 \div 2]\sigma$ excess within this scheme.

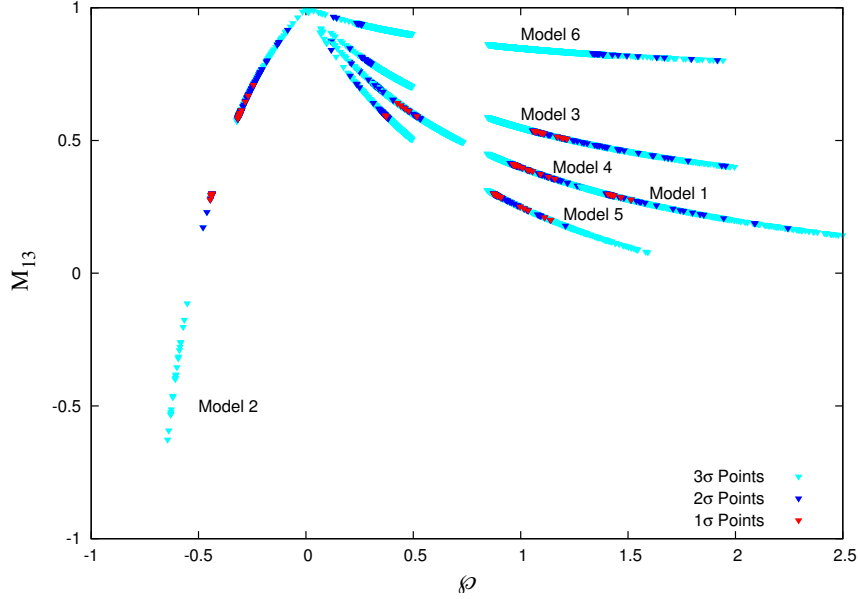


Figure 6.8. The variations of mixing parameter φ with M_{13} for different set of models leading to $[1 \div 3]\sigma$ excess in muon (g-2). The other models cannot provide Δa_μ excess at level of $[1 \div 2]\sigma$.

because both are related for specific models. Around that solution, where M_{23} or M_{13} is very small, no parameter space is compatible with other imposed constraints. We have also explicitly shown the dependence of excess of muon (g-2) on the weighted mixing φ .

7 Conclusion

High scale supersymmetry breaking is at the center of study since long time due to its minimalistic view. In this paper we have adopted a methodology to understand the correlations among high scale parameters in these type of scenarios, with a goal to explain the $[1 \div 3]\sigma$ excess of muon (g-2) over Standard Model predictions. To enrich the viability of our analysis, we have carefully incorporated the collider constraints without being biased to any particular scenario and also avoided the implementation of just mSUGRA bounds. The experimental constraints coming from simplified model assumptions have been tuned suitably. Hence the constraints imposed in our analysis can be taken over *mutatis mutandis*.

We have categorized our work in two parts: first we have discussed the model independent correlations among non-universal gaugino masses, and found out the muon (g-2) compatible solutions at $[1 \div 3]\sigma$ level. We observe that none of the existing models' predictions fit within this. Thus from muon (g-2) point of view, these models are not capable enough. We have further analysed the high scale parameter space in terms of the low scale masses of sleptons, smuons, lighter chargino and lightest neutralino (LSP), along with $\tan\beta$. Then we have also scrutinized such parameter space in the light of direct and indirect searches for DM. We have encompassed that regime by showing the dependence of relic density and spin dependent cross-section (σ_{SI}) on mass of the DM.

We have briefly discussed the general structure of the gaugino masses that include the contributions from singlet and non-singlet chiral super-fields. Thus in such cases there is an extra parameter which is a measure of mixing of contributions from both fields. We have stuck to minimal models, i.e., restricted to one non-singlet field and explored the range of that mixing parameter from muon (g-2) viewpoint along with other constraints. We have found only few of the existing models can explain the excess in Δa_μ at $[1 \div 2]\sigma$ level.

In summary, we have captured the model independent features of non-universality considering muon (g-2) excess on a serious note. This broadly classified picture is also grabbed for some particular cases in terms of some specific benchmark points.

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